

Software Development Experience in Designing of Steel Structural Joints

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ABSTRACT

The paper presents **COMET** software which enables to design steel structural joints widely used in civil and industrial engineering.

The conceptual basis of the project was the idea of creating a program with the following functions: automatic determination of all parameters of the joint which formally satisfies the requirements of design codes for the given internal forces combinations; automatic determination of some parameters of the joint, taking into account the fact that other parameters are specified by the user and can not be changed; implementation of all control verifications of whether the load-bearing capacity constraints as well as structural constraints are satisfied in the cases when all parameters of the joint are specified and can not be changed.

Algorithm for designing each joint prototype has been presented as a set of operations implementing the rules for determining the interrelated values of the joint parameters. Each prototype is developed as an independent program that performs a full cycle of designing the joint and verification of the joint parameters according to the specified design codes.

Searching of unknown joint parameters has been transformed to a decision making problem based on analysis of the joint mathematical model. Automatic searching of unknown joint parameters has been implemented as a multiple targeted improvement of a certain initial joint design in order to satisfy load-carrying capacity constraints taking into account the structural and assortment-based constraints. Multiple improvement of current joint design is performed on the basis of sensitivity analysis relative to variation of governing joint parameters.

In cases when the values of some joint parameters have to be taken as fixed (or user-defined), the program considers these parameters as the same kind of initial data. All other (unknown) parameters will be considered as design variables of the searching problem. Thus, the technology implemented in **COMET** supports the mode of active user decision making.

INTRODUCTION

Design and analysis of joints is one of the most important stages of design of steel structures. Unlike the stress-strain state analysis on the basis of the design model, which follows the strict rules of structural mechanics, "algorithms" for the analysis of joints use the traditional methods (taking into account the previous experience) of approximate solutions, which are based on a simplified representation of the behavior of joints. These methods are usually closely related to the set of proven designs of joints (prototypes) used for this type of structures.

Despite the variety of prototypes of joints of one type (for example, columns bases), the number of parameters that have to be determined for each of them in the design process is limited. Taking into account the peculiarities of the behavior of a certain prototype of the joint in the structure (e.g., the cross sections of structural elements coming into the joint, loads taken by the joint etc.), and the requirements of various design codes, the algorithm for designing each joint prototype should be presented as a set of operations implementing the rules for determining the interrelated values of the parameters. Each prototype is developed as an independent procedure that performs a full cycle of designing the joint, check of the parameters according to the specified design codes, as well as the generation of a drawing of the designed joint. Taking into account the fact that regardless of the selected prototype most of the parameters of the same purpose of the joints of the same type are determined according to the same rules, the software implementation of parametric prototypes comes down to the organization of information exchange between different software modules that serve to determine the specific parameters.

The focus on the use of parametric prototypes of joints that meet the above requirements has been adopted in the first programs developed by SCAD Soft Ltd. since the mid-1990s and implemented in software **COMET** (Karpilovsky *et al.* 1998). A similar approach to the solution of the problem of designing steel structural joints has been also used by other developers of CAD-CAE systems, for example, **RFEM** and **RSTAB** modules of Dlubal Software (JOINTS 2015), **Connections** modules of

Autodesk Robot Structural Analysis Professional (Sukhorukov 2009) or **STK-SAPR** and **ESPRI** of LIRA-SAPR.

CRITERIA FOR SELECTING PROTOTYPES FOR THE DEVELOPMENT

On the one hand, the set of parametric prototypes defines the scope of the program, and the cost and time for its development on the other hand. There are no strict rules for selecting the prototypes, and in the case of **COMET** it entirely depended on the developers' experience.

The complexity and high cost of the development of this kind of software have defined the search for designs of joints that would both meet the criteria of mass use in the design practice and provide the possibility to analyze joints which might be not the most common, but are quite difficult for most designers of joints, as one of the most important problems.

The first criterion satisfies the business considerations of CAD-CAE system developers since the mass use of such joints in the design provides the popularity of the program among ordinary designers. On the other hand, joints which might be not that common, but require highly skilled designers and create certain engineering problems, increase the rating of the software and the authority of the developers, which ultimately affects the commercial component of all the company developments.

Column bases (rigid and nominally pinned) are an example of joints which satisfy the criteria of mass use, at the same time the software also enables to analyze and design various types of beam splices with end-plates since it is very difficult for most designers.

Regardless of the criteria for the selection of certain joints in parametric prototypes, a proper design study is an absolute requirement because the program operates only with the design details provided in advance at the algorithm development stage.

It should be noted that the design model of the joint is largely defined by the existing traditions of designing. "Traditional" models are often very rough, since they were developed during the period of "manual" design demanding maximum simplification of the problem. Mass transition to the CAD-CAE design systems enables to use more accurate design models, however the results of such a "clarification", often resulting in complication of the joint, may require additional studies.

In some cases, this kind of clarification is inevitable. For example, the traditional calculation methods given in the codes are not always suitable for solving three-dimensional problems. In particular, it concerns rigid column bases for which the problem of determining the contact area of the base plate with concrete arises at bending in both principal planes. The internal solver of **COMET** uses the finite element method to solve this problem.

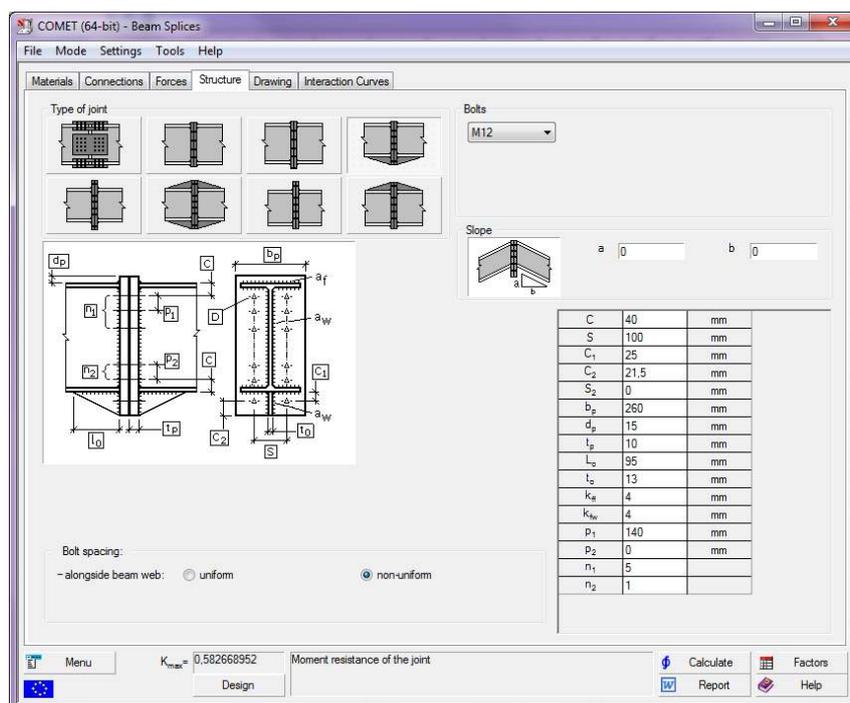


Figure 1. Set of prototypes of the design of beam splices

PARAMETRIC PROTOTYPES ORIENTATION AND ROLE OF A DESIGNER

The current version of **COMET**, which will be further considered, enables to design steel structural joints widely used in civil and industrial engineering (Karpilovsky *et al.* 2010), (Perelmuter *et al.* 2010). The application is also used to perform a structural appraisal of a steel joint according to the requirements of Ukrainian codes (DBN B 2.6-163: 2010 or DBN B 2.6-198: 2014), Russian codes (SNiP II-23-81*, SP 53-103-2004 or SP 16.13330.2011) and European codes (EN 1993-1-8, EN 1993-1-1). Among other things, the selection of codes defines the set of prototypes of joints proposed for the analysis, which includes only the joints that are reflected in the text of the codes.

The **COMET** software provides the following groups of prototypes for steel structural joints: nominally pinned and rigid column bases, beam and rafter splices, hinged and rigid joints between columns and rafters, and truss joints.

The set of parametric prototypes for each type of joint has been determined on the basis of different requirements, the consideration of which has affected not only the selected designs, but also the parameters necessary for their implementation.

A set of prototypes implemented for beam splices is given as an example in Fig. 1.

The joint prototype is selected by the designer. Only formal checks are performed at the stage of the data input (e.g. correspondence of the set of force factors to the selected joint prototype). Once the calculation is completed, it is up to the designer whether to accept or reject the analyzed design. Given that the time of the calculation of joint is comparable with the time it takes to press a "button" invoking this operation, it becomes possible to analyze other options and make a justified decision.

INPUT AND CONTROL OF THE INITIAL DATA

Initial data include the information about the structural members connected in the considered joint, their sections and steel grades, joint's type (prototype), set of internal forces acting in adjacent sections of the connected members as well as the data allowing to select the properties of the used bolted and welded connections (Fig. 2).

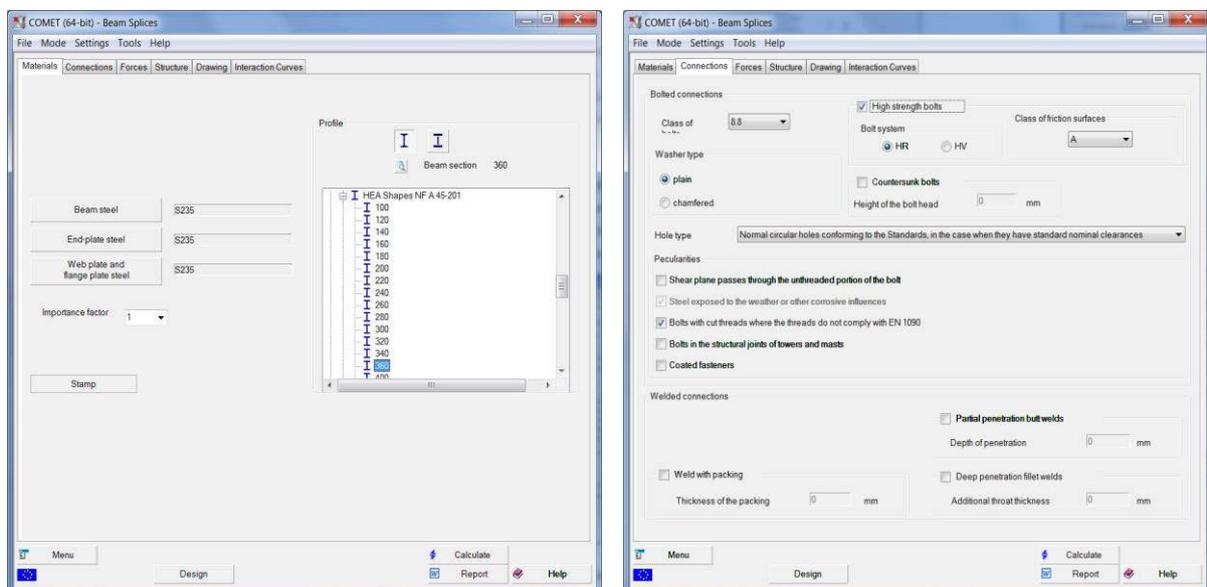


Figure 2. Dialog boxes for specifying the main initial data

Taking into account the fact that the joint has to work in different design situations, the program enables to specify the necessary number of internal forces combinations. These combinations can be specified by the user or be the result of the calculation performed by structural analyzer SCAD. The main requirement is the simultaneous action of forces included in one combination.

The check of the initial data is performed by the program both in the process of their specification (detection of formal errors) and in the design process. Diagnostic messages are generated on the basis of the check results.

SOFTWARE IMPLEMENTATION

Conceptual provisions and flowchart

The conceptual basis of the project was the idea of creating a program with the following functions:

- automatic determination of all parameters of the joint which formally satisfies the requirements of design codes for the given internal forces combinations;
- automatic determination of some parameters of the joint, taking into account the fact that other parameters are specified by the user and can not be changed;
- implementation of all control verifications of whether the load-bearing capacity constraints as well as structural constraints are satisfied in the cases when all parameters of the joint are specified and can not be changed.

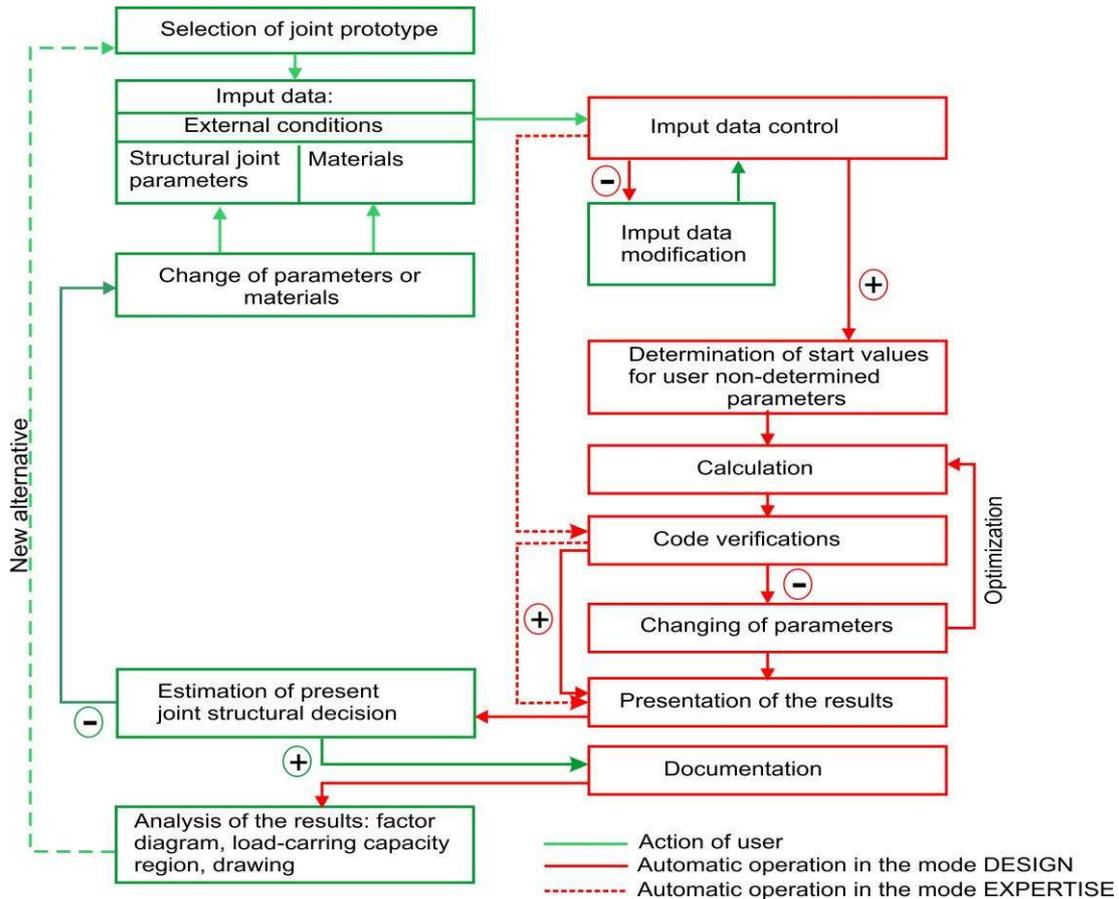


Figure 3. Generalized flow chart in the designer-software interaction mode

In fact, the role of the program can change from the "generator of all parameters" of the design specified by the user, taking into accounts the codes and external factors to the "simple check" of the capacity of the joint in accordance with the codes (the check of the parameters specified by the user). In cases when the values of some parameters have to be taken as fixed (user-defined), and all others are determined by the conditions of compliance with the codes, the program works according to the second variant. The program considers the parameters specified by the user as the same kind of initial data like the class of concrete or steel grade.

A generalized flowchart for solving the problem in the designer-software interaction mode corresponding to this concept is shown in Fig. 3.

A role of the structural engineer is an important feature of the concept of searching/checking the parameters of the joint adopted in the program. He is responsible for the choice of the design, completeness and correctness of the loads taken into account and acting on the structure with the considered joint, as well as the analysis of the applicability of the obtained solution. If in the result of the analysis the designer changes some parameters, the program will perform the check and the

search for such values of other parameters that would ensure the operation of the joint and would not contradict the codes.

Software modes

As noted above, the program enables to select the parameters of the joint on the basis of the design selected by the user and the conditions of its reliability and operability under the given operating conditions and materials (Fig. 4).

If the joint is already operating in the real structure, i.e. all its parameters and operating conditions are known, the check of the joint can be performed, the results of which enable to make a justified decision about the possibility of the operation of the joint in the new conditions (for example, at high loads on the structure).

Thus, two fundamentally different modes have been implemented in the program – **Design** and **Calculate**, which are invoked by the respective buttons.

If in the result of the design the parameters of the prototype provide the operability of the joint, but some of them can not be accepted because of the (possibly not formalized) requirements the designer knows, the list of the initial data can be extended by specifying the desired values for such parameters. At the same time, all other parameters not subject to the above requirements are set to zero and the design mode repeats.

When setting the parameters the program analyzes their values and reports detected violations of the design requirements. These can be strict guidelines on the need to change the specified values, or warnings about the violation of the recommendations of codes that can be ignored.

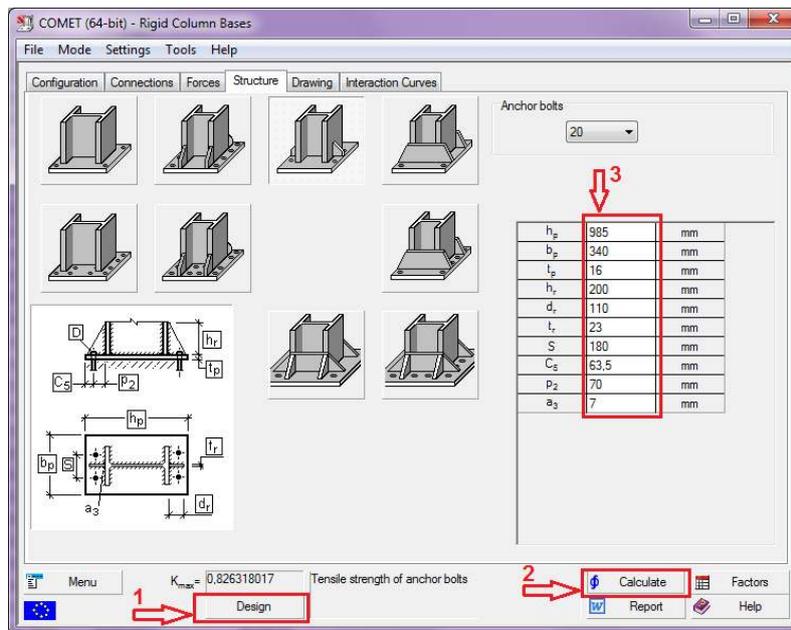


Figure 4. Control of the software mode: 1 - determination the preliminary design decision, 2 - calculation of variable parameters and verification of the design decision, 3 – specification of the values for user-determined (fixed) parameters

Thus, the technology implemented in **COMET** supports the mode of active user decision making. Such a mode can both satisfy an experienced designer allowing him to achieve the necessary solution, and allow the beginner to solve a design problem with minimal interference in the decision-making process.

Solution optimization

If the design check indicates the need to change the design parameters, this change is performed in the program on the basis of the sensitivity analysis. The idea of this approach is considered below.

Inequalities of the type $E_{d,i} \leq R_{d,i}$ should be satisfied in all checks between the design values of the action effects $E_{d,i}$ and the design strength $R_{d,i}$ according to the limit state calculation method adopted in EN 1990. It is more convenient to represent these inequalities in the following form:

$$k_i = E_{d,i}/R_{d,i} \leq 1,0 \quad (i = 1, \dots, n) \quad (1)$$

where k_i is the utilization factor of the i^{th} constraint, it is the reciprocal of the factor of safety. The value of the factors k_i is a function of the governing design parameters X_j ($j = 1, \dots, p$).

It should be noted that not all design parameters are independent. Some of them can be considered as governing, while others are unambiguously calculated at the known values of the governing parameters, and are not considered further. Moreover, some values of the parameters can be forced by the user; they are fixed and are not considered in the following description as well.

Automatic selection of the unknown values of the internal parameters of a joint design is implemented as a multiple targeted improvement of a certain initial design of the joint in order to satisfy the bearing capacity limitations taking into account the structural and assortment limitations. Multiple improvement of the design is performed on the basis of the analysis of its sensitivity to variation of the controlled parameters of the joint design. The response of the system, the values of the utilization factors of the load-bearing capacity constraints, is evaluated at each variation of a certain controlled parameter.

Let's consider the case when it is necessary to improve the design that does not satisfy the requirements of the codes, since its check has shown that some of the inequalities (1) are violated and the utilization factor of the constraints is greater than one. If an increment ΔX_s is given to one of the parameters, for example X_s , all utilization factors can change obtaining new values $k_{is} = k_i + \Delta k_{is}$. It is logical to first use the change of the parameter ΔX_r for which the value of the greatest utilization factor of restrictions improves the most, i.e. $k_{jr} = \min_{s=1, \dots, p} \max_{i=1, \dots, n} (k_i + \Delta k_{is})$.

The problem can be simplified in certain situations:

- if a certain constraint utilization factor depends not on all governing parameters, the increments of the parameters which do not affect it are not checked;
- if different utilization factors depend on different groups of governing parameters, the problem is divided into a number of unrelated sub-problems.

PRESENTATION OF RESULTS

Results of the design and verification are given as a diagram of checked factors, drawing with a preliminary design of the considered joint, a family of graphs bounding the region of the load-bearing capacity of the joint in the coordinate system of the selected internal forces and the report in RTF-format.

Factors diagrams

Results of the load-bearing capacity verifications for compliance with the requirements of design codes are given in the form of a factors diagram. Each factor is accompanied by a reference to the respective section of the code which regulates these requirements. The values of the factors are given in the form of the constraint utilization factors.

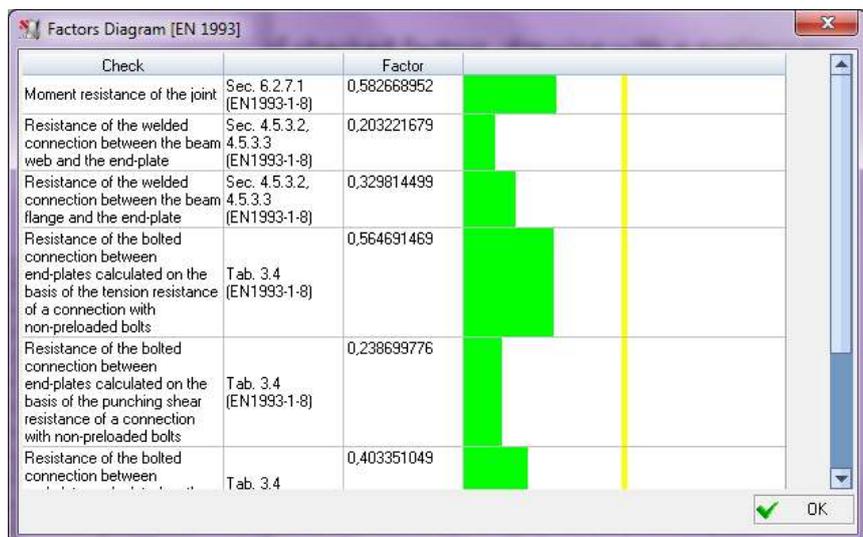


Figure 5. Factors diagram

Drawing

A graphical representation of the designed joint is given in the form of a simplified drawing, which describes the structure completely and in detail, including the specification (Fig. 6), but it does not take into account the manufacturer's technical requirements. In order to correct the drawing it can be presented in DXF-format, a file that can be used by various graphic editors.

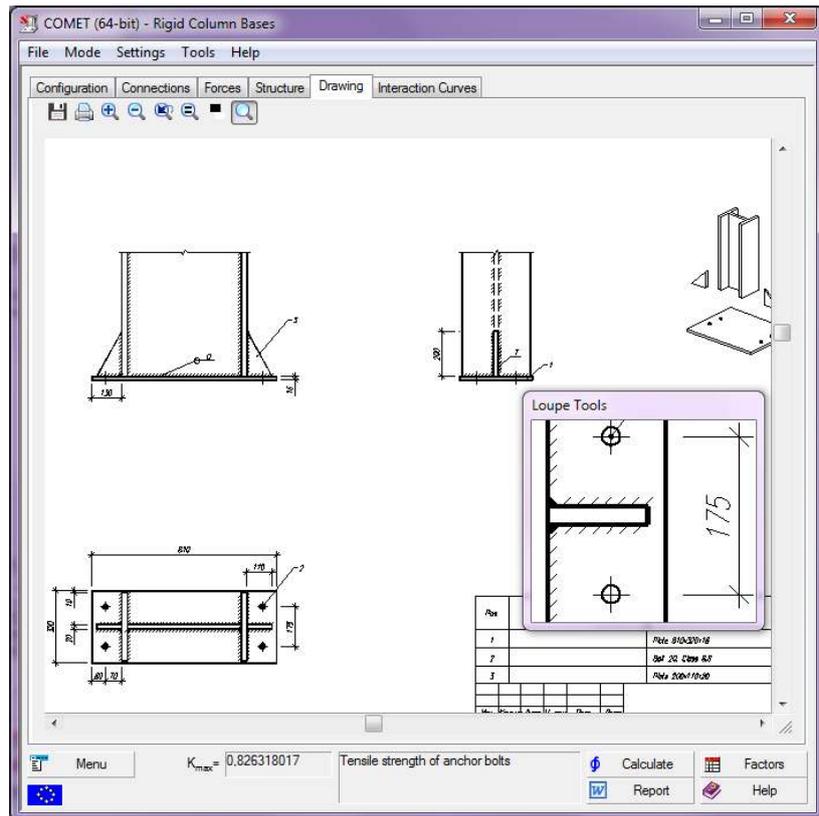


Figure 6. Design drawing on the screen

Load-bearing capacity regions for the joint

Load-bearing capacity region for the structural joint is a family of graphs in the coordinate system of the selected internal forces bounding the region where all utilization factors are less or equal to one or, by other words, where all inequalities (1) are satisfied (see Fig. 7). Such family of graphs gives us a representation of the load-bearing capacity of the designed joint in terms of the selected design code. Plotting each variant of such a region deals with a design verification of hundreds of internal forces combinations. It seems to us that such a large-scale verification has never been performed before.

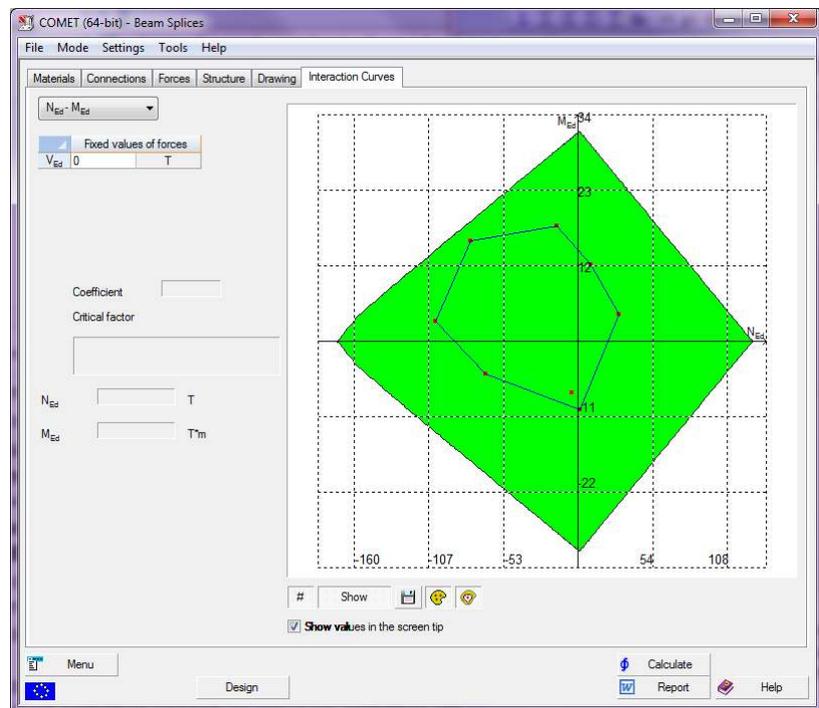


Figure 7. Plotting the load-bearing capacity region together with points corresponded to the acting internal forces in the joint and convex shell of internal forces

The program also enables to show the position of points corresponding to the internal forces and to plot a convex shell on the basis of these points thus bounding the part of the load-bearing capacity region, which corresponds to any linear combination of design internal forces in the considered joint.

Fig. 8 shows variants of the load-bearing capacity region for different type of beam splices designed for the same set of internal forces. It can be seen in this case that the selection of the prototype has affected on the shape of the load-bearing capacity region.

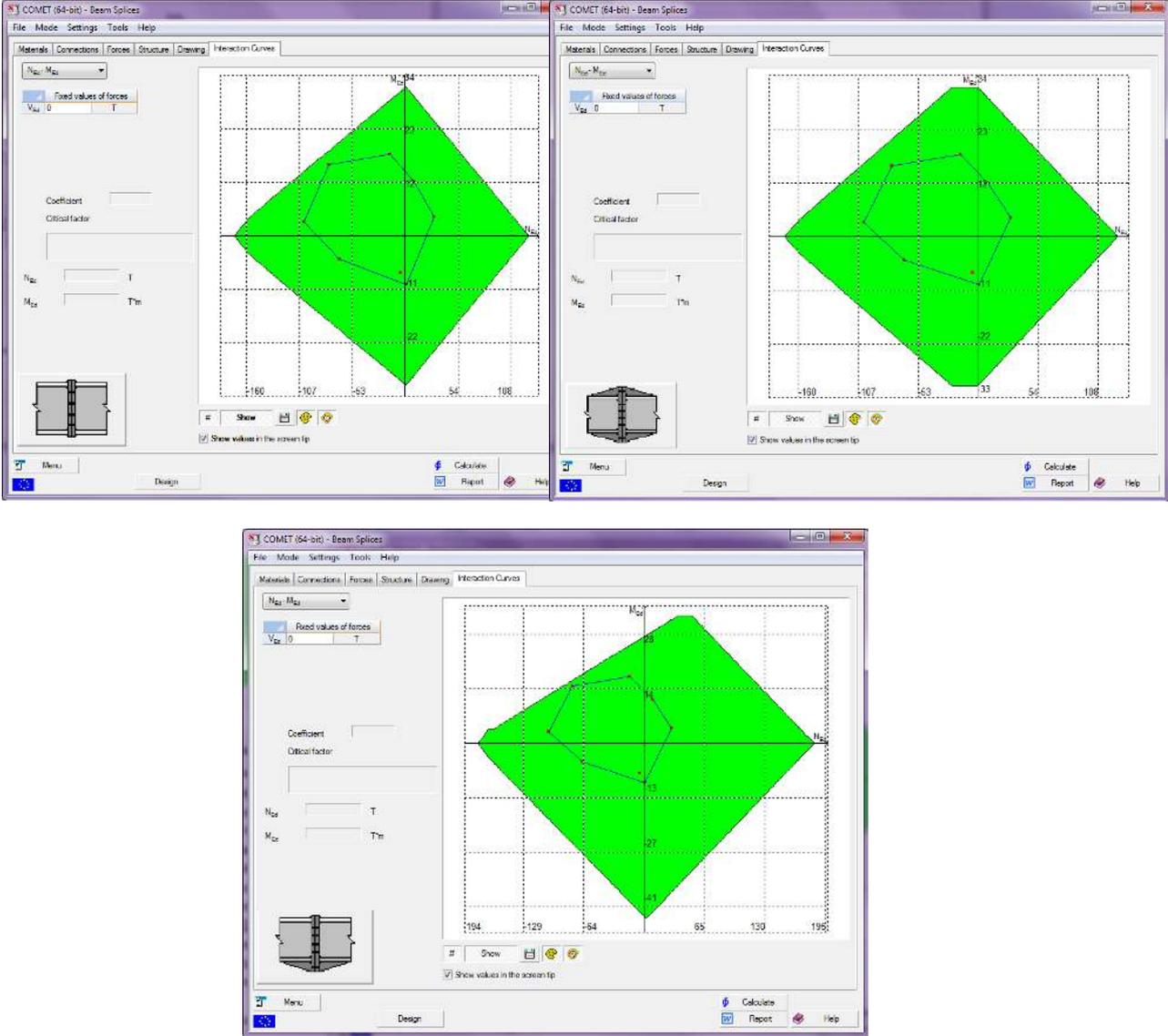


Figure 8. Variants of the load-bearing capacity regions for different types of beam splices joint

CONCLUSIONS

The paper presents **COMET** software with the following functions: automatic determination of all parameters of the joint which formally satisfies the requirements of design codes for the given internal forces combinations; automatic determination of some parameters of the joint, taking into account the fact that other parameters are specified by the user and can not be changed; implementation of all control verifications of whether the load-bearing capacity constraints as well as structural constraints are satisfied in the cases when all parameters of the joint are specified and can not be changed.

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